A strategy for human-robot collaboration in taking products apart for remanufacture

Huang, Jun; Pham, Duc; Wang, Yongjing Wang; Ji, Chunqian; Xu, Wenjun; Liu, Quan; Zhou, Zude

DOI:
10.5937/fmet1904731H

Jun Huang
Postdoctoral Research Fellow
University of Birmingham
Department of Mechanical Engineering
United Kingdom

Duc Truong Pham
Professor
University of Birmingham
Department of Mechanical Engineering
United Kingdom

Yongjing Wang
Research Fellow
University of Birmingham
Department of Mechanical Engineering
United Kingdom

Chunqian Ji
Research Fellow
University of Birmingham
Department of Mechanical Engineering
United Kingdom

Wenjun Xu
Professor
Wuhan University of Technology
School of Information Engineering
China

Quan Liu
Professor
Wuhan University of Technology
School of Information Engineering
China

Zude Zhou
Professor
Wuhan University of Technology
School of Information Engineering
China

A Strategy for Human-Robot Collaboration in Taking Products Apart for Remanufacture

Using humans and robots working together to disassemble end-of-life (EoL) products so that they can be remanufactured enables catering for the effects of uncertainties in the condition of those products and unpredictability in remanufacturing operations. Collaborative robots are one of the key elements of Industry 4.0. This paper presents a strategy for human-robot collaborative disassembly that exploits the active compliance control capability of collaborative robots. The paper outlines the proposed human-robot collaboration strategy and active compliance control. It then presents a case study of robotic disassembly designed to show a practical implementation of the proposed strategy to take products apart. The study involved the dismantling of an automotive water pump by a collaborative industrial robot working with a human operator and by two collaborative robots and a human operator. Active compliance control was implemented to separate press-fitted components from the water pump. The results demonstrate the feasibility of the strategy and its effectiveness at increasing flexibility and adaptability by reducing setup efforts.

Keywords: *Industry 4.0, remanufacturing, robotic disassembly, human-robot collaboration, collaborative robot, active compliance control.*

1. INTRODUCTION

Remanufacturing is increasingly important to delivering economic and environmental benefits in a circular economy [1-4]. Autonomous remanufacturing reduces costs and makes remanufacturing viable for a wider sector of industry. Disassembly automation is critical to enabling autonomous remanufacturing [5, 6]. The main technical barrier to autonomous disassembly comes from uncertainties in the condition of returned EoL products and the associated unpredictability in remanufacturing operations [7-9]. Semi-autonomous disassembly using human-robot collaboration (HRC) could provide the flexibility needed to handle such uncertainties and unpredictability [10]. In human-robot collaborative disassembly, robots and human operators work side by side to perform joint or independent disassembly tasks without traditional safety guarding.

There has not been much reported research into using HRC in disassembly. A systematic framework for the implementation of human-robot collaborative disassembly was presented for sustainable manufacturing [11]. A workstation employing a collaborative robot as an assistant for a human operator was presented for the disassembly of electric vehicle batteries [12, 13]. In the workstation, the human operator performed complex tasks, and the robot handled simple and repetitive tasks. Collaborative robots were applied to classify and dismantle e-waste [14]. In a common workspace, humans identified complex materials and components, and robots carried out heavy and dangerous tasks. An informed software agent was developed for HRC to increase efficiency and improve ergonomics in disassembly processes [15]. A method to assess manufacturing capability was investigated for HRC disassembly [16]. A flexible multi-sensorial system was proposed for robotic disassembly using collaborative robots [17]. The system was validated on the disassembly of CD drivers, battery covers and electronic circuits. In addition, human robot collaboration was implemented in the assembly of aircraft structures to optimise aircraft production [18].

Active compliance control can enable collaborative robots to avoid colliding with and injuring humans. It gives robots the flexibility and adaptability needed to achieve complex tasks [19]. For instance, to handle workpiece variances, active compliance control was implemented in industrial processes such as grinding, polishing and deburring. Active compliance control was

Received: November 2018, Accepted: June 2019
Correspondence to: Dr Jun Huang
Department of Mechanical Engineering, University of Birmingham, Birmingham B15 2TT, United Kingdom
E-mail: j.huang.1@bham.ac.uk
doi:10.5937/fmet1904731H

also employed for industrial finishing operations using HRC with a collaborative robot [20]. To handle uncertainties in the environment and workpieces, active compliance control was used for surface-surface alignment tasks [21]. Active compliance control was applied to enable a robot to assist surgeons in the execution of knee surgery resections [22].

This paper presents a strategy suitable for HRC disassembly in remanufacturing. The proposed strategy uses the active compliance control facility of the robot to achieve complex disassembly tasks. The paper is organised as follows. Section 2 introduces the state of the art in HRC disassembly. An outline of active compliance control follows in Section 3. Section 4 describes a case study showing an implementation of the strategy. Section 5 concludes the paper.

2. HRC DISASSEMBLY

Currently, most disassembly operations in remanufacturing are performed manually, which results in low efficiency and high labour cost [10]. Although fully automated disassembly could deal with large volumes, it lacks flexibility and requires high capital investment. Fully automated disassembly is unable to handle the uncertainties and variances associated with EoL products and disassembly processes [23, 24]. HRC disassembly, a semi-autonomous disassembly method, has greater potential to afford both efficiency and flexibility.

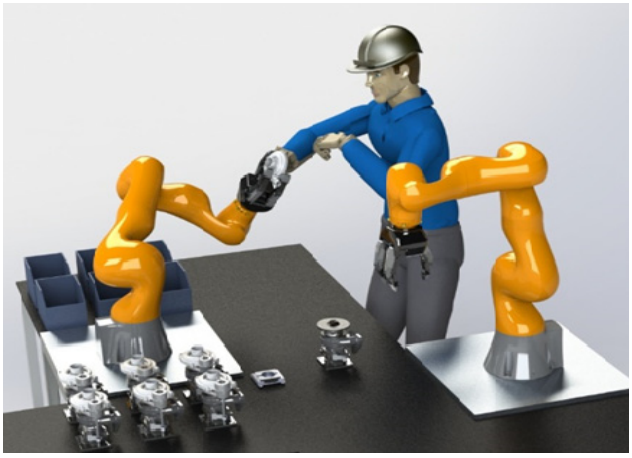

Figure 1. Human-robot collaborative disassembly cell [25].

In HRC disassembly, robots and other ancillary equipment carry out tasks that are repetitive, heavy and dangerous, leaving people to assume a supervisory role or perform work that requires greater dexterity, flexibility or cognitive ability than robots or machines can provide. In other words, the strength, precision and repeatability of robots and human know-how, manual flexibility and dexterity could be combined. In that way, human operators can handle the uncertainties and variances associated with EoL products and disassembly operations with lower equipment investment compared with fully automated disassembly. Figure 1 illustrates an example of a HRC disassembly cell. Without physical barriers such as safety cages, the cell enables human operator and robots to work together and interact safety in a shared workspace to perform their tasks jointly or independently.

To achieve HRC, robot manufacturers have produced collaborative robots ("cobots") capable of working alongside people without having to be fenced in safety cages. Table 1 lists five representative industrial collaborative robots on the market and their specifications. In addition, AURA from COMAU, as one of the largest cobots, has a payload of 170 kg and a reach of 2.8 m [26]. The International Federation of Robotics reported that cobots were an important element of Industry 4.0 and were expected to account for 34% of all robot sales on the market by 2025 with an annual demand growth of 60% [27]. Cobots provide manufacturers with more flexible automation solutions which can easily and quickly be adapted to meet shifting demands with an economic investment cost. The combination of humans' experience and cognitive abilities and robots' strength, dependability, reach and endurance will significantly facilitate applications of human-robot collaboration [28].

Table 1. Five representative industrial collaborative robots on the market and their specifications.

Company	ABB	FANUC	KUKA	STAUBLI	UNIVERSAL ROBOTS
Type	YuMi IRB 14000	CR-35iA	Iiwa 14 R820	TX2-90	UR10
Degree of freedom	7	6	7	6	6
Payload (kg)	0.5 per arm	35	14	14	10
Reach (mm)	559	1,813	820	1,000	1,300
Repeatability (mm)	0.02	± 0.04	± 0.15	± 0.03	± 0.1
Installation	Table	Floor	Floor/ Wall/Ceiling	Floor/ Wall/Ceiling	Any
Weight (kg)	38	990	30	117	28.9

3. ACTIVE COMPLIANCE CONTROL

Compliance helps robots to mitigate the effects of position and velocity errors and handle uncertainties in the location, size and shape of the workpiece [29]. Robot compliance can be active or passive [30]. Table 2 lists the key features of active and passive compliance [31, 32]. Active compliance is software-based. Therefore, it is more easily adapted to different situations and was adopted for this application.

Active compliance control enables robots to interact with human operators safely and achieve complex tasks such as assembly and disassembly [33]. For example, the end effector of a compliant robot can move to different positions and exert different forces on an object depending on external conditions.

Hybrid position/force control and impedance control are two approaches to achieving active compliance control [21]. Hybrid position/force control combines force and torque information with positional information to satisfy simultaneous position and force trajectory constraints in a convenient task-related coordinate system

[34]. Impedance control is adopted to produce a certain desired dynamic behaviour of the robot when it interacts with the environment. Stiffness and damping coefficients are important parameters in active compliance control.

Table 2. Key features of active and passive compliance [31].

Active compliance	*Passive compliance*
Mainly software based	Mainly hardware based
Easy to compute and regulate	Difficult to compute and regulate
Can be of general use	Normal, dedicated to an application
Compliance centre can be shifted	Compliance centre is normally fixed
Dynamic compliance	Static compliance
Instability may occur	Overall stability is guaranteed
May be affected by kinematic singularities	Kinematic singularities are not applicable
Costly	Relatively cheap
Relatively simple structure	Mechanically more complex

Having a controllable stiffness enables a collaborative robot to perform precise tasks with high stiffness (in the stiff mode) and safely collaborate with humans with low stiffness (in the compliant mode). In the compliant mode, the robot can avoid hard collisions with humans by reducing impact forces during physical interaction [35].

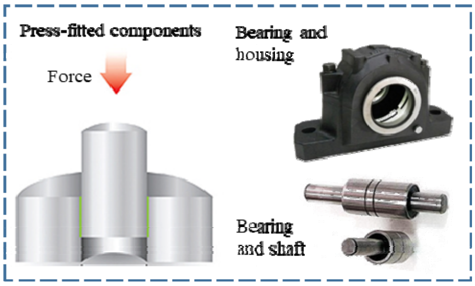

Figure 2. Disassembly of press-fitted components.

As shown in Figure 2, parts or components (such as bearing-housing, and bearing-shaft) are often assembled with an interference fit by a press force. To disassemble the press-fitted components, a press can be employed used to apply a force on one of the components. With active compliance control, collaborative robots can be used to hold the component to be pressed out during the disassembly process and follow its movement until it is separated completely, releasing human operators for other disassembly tasks.

4. CASE STUDY

To demonstrate the proposed strategy and method for human-robot collaborative disassembly, a case study was conducted in the authors' Autonomous Remanufacturing Laboratory. The case study involved the robotic disassembly of an automotive water pump. The press-fitted components in the water pump were separated by HRC using collaborative robots with active compliance control.

2.1 HRC disassembly cells

As shown in Figure 3, the first HRC disassembly cell consists of a collaborative robot (KUKA LBR iiwa 14 R800) fitted with a two-fingered gripper (Robotiq 2-FINGER 140), a small manual press, the press operator, the water pump to be disassembled plus positioning jigs and part collection boxes located on a workbench. The robot can work under impedance control using a Cartesian impedance controller with configurable stiffness and damping. The configurable spring stiffness ranges for the translational and rotational degrees of freedom are 0 - 5000 N/m and 0 - 300 Nm/rad, respectively [36]. The robot uses the gripper to handle the pump components and positioning jigs. The collection boxes keep the different dismantled pump components separated from one another.

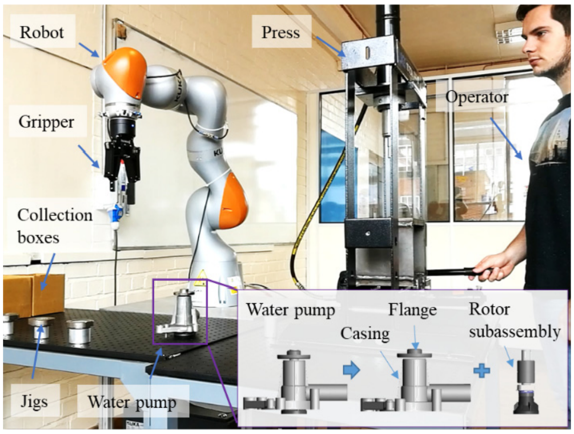

Figure 3. First HRC disassembly demonstration cell with a collaborative robot.

The water pump was a Unipart GWP187. As illustrated in Figure 3, the pump comprises a flange, a pump casing and a rotor subassembly, which contains a bearing, a shaft, a seal unit, and an impeller. The material of the flange, shaft and bearing is steel. The material of the pump casing is aluminium alloy. The fit between the flange and rotor and between the pump casing and rotor subassembly is press fit.

Figure 4 shows another HRC disassembly cell with two industrial collaborative robots (KUKA LBR iiwa 14 R800). Robot-1 is equipped with a two-fingered gripper (Robotiq 2-FINGER 140). Robot-2 has a three-fingered gripper (Robotiq 3-FINGER adaptive robot gripper). The disassembly tasks were assigned among Robot-1, Robot-2 and a human operator. The proposed strategy and method of taking press-fitted components apart was implemented and tested in the above two robotic disassembly cells.

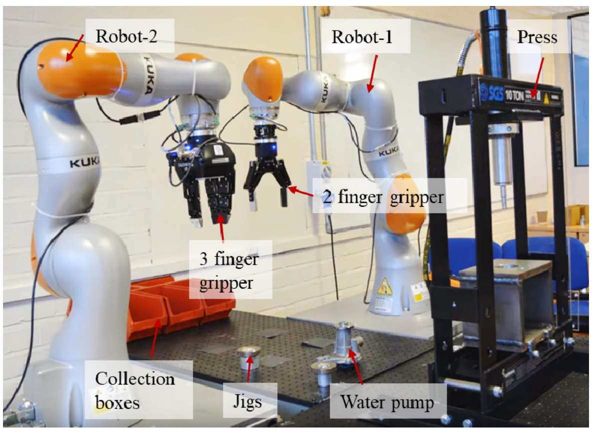

Figure 4. Second HRC disassembly demonstration cell with two collaborative robots.

2.2 Cell HRC disassembly tasks

The separation of the rotor subassembly from the flange and the pump casing is one of the collaborative tasks in the disassembly of the water pump. As illustrated in Figure 3 and Figure 5, the collaborative disassembly task involved the operator using the press to apply the required separation force, with one part remaining in the press while the robot holds the other and follows its movement as it is being pushed out.

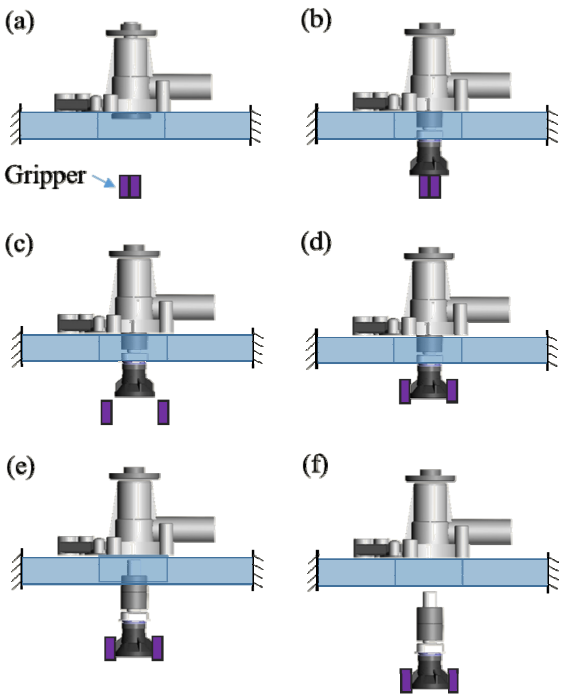

Figure 5. Procedure of separating rotor subassembly from flange and pump casing.

The details of this separation procedure are illustrated in Figure 5 and Figure 6. Figure 5(a) shows the robot gripper at a set position under the water pump as the robot waits for the rotor subassembly to be pushed out of the flange and the pump casing. When the robot detects an increase in the vertical component of the force on its gripper caused by the rotor subassembly touching it (as shown in Figure 5(b)), the robot moves the gripper down slightly to be clear of the rotor subassembly and then opens the fingers (as shown in Figure 5(c)). Figure 5(d) depicts the gripper moved back up to grasp the rotor subassembly. In Figure 5(e), the robot has taken hold of the rotor subassembly and turned on the compliant mode to enable the gripper passively to follow the downward movement of the rotor subassembly. When the rotor subassembly has been separated completely as shown in Figure 5(f), leaving the flange resting on the casing in the press, there is a step change in the vertical force on the gripper due to the weight of rotor subassembly, which it now carries. This causes the position of the gripper to drop sharply. At that point, the robot switches off the compliance mode and the procedure ends.

The related robot control program is shown in Table 3 for separating the rotor subassembly from the flange and the pump casing. The program is written in Java using the KUKA Sunrise Workbench [36].

Table 3. Robot control program.

Input: external force by contact on robot manipulator
Output: finishes wait state, grasp and follow the movement of the rotor subassembly

```
private void HRCAB(String P1, String P2, String
  P3, String P4, String P5) {
   Safeptp(P1);
   Gripping();
   Safelin(P2);
   waitingforce(1.0, P2);
   Safeptp(P3);
   Grippos(117);
   Safelin(P4);
   Gripping();
   newstiffness(220.0);
   Safeptp(P5);}
  private void waitingforce(double forcevalue, String
   WP2){
    int sell = 0;
    ForceSensorData data =
       robot.getExternalForceTorque(robot.getFlange());
    Vector force00 = data.getForce();
    double forceInz = force00.getZ();
    double forceInz11 = forceInz - forcevalue;
    do {Safeptp(WP2);
      ForceSensorData data1 =
      robot.getExternalForceTorque(robot.getFlange());
    Vector force01 = data1.getForce();
    double forceInz1 = force01.getZ();
    if(forceInz1 < forceInz11){sell = 1;}
    } while (sell == 0);}
    private void newstiffness(double positionvalue) {
    getLogger().info("Stiffness");
    int answer = 0;
    double stiffX = 300.0;
    double stiffY = 300.0;
    double stiffZ = 300.0;
   CartesianImpedanceControlMode modeHand = new
   CartesianImpedanceControlMode();
modeHand.parametrize(CartDOF.X).setStiffness(stiffX);
modeHand.parametrize(CartDOF.Y).setStiffness(stiffY);
modeHand.parametrize(CartDOF.Z).setStiffness(stiffZ);
   modeHand.parametrize(CartDOF.ROT).
   setStiffness(100.0);
   IMotionContainer handle;
 handle = nase.moveAsync(positionHold(modeHand, -1,
     TimeUnit.SECONDS));
   do{Frame cmdpos =
  robot.getCurrentCartesianPosition(robot.getFlange());
   double value = cmdpos.getZ();
   if(value < positionvalue){answer = 1;}
     } while (answer == 0);
    handle.cancel();}
```

Table 4. Robot stiffness during disassembly process.

Disassembly process	Translational stiffness (N/m)			Rotational stiffness (Nm/rad)		
	X	Y	Z	A	B	C
Figure 5(a)	2000	2000	2000	200	200	200
Figure 5(b)	2000	2000	2000	200	200	200
Figure 5(c)	2000	2000	2000	200	200	200
Figure 5(d)	2000	2000	2000	200	200	200
Figure 5(e)	300	300	300	100	100	100
Figure 5(f)	300	300	300	100	100	100

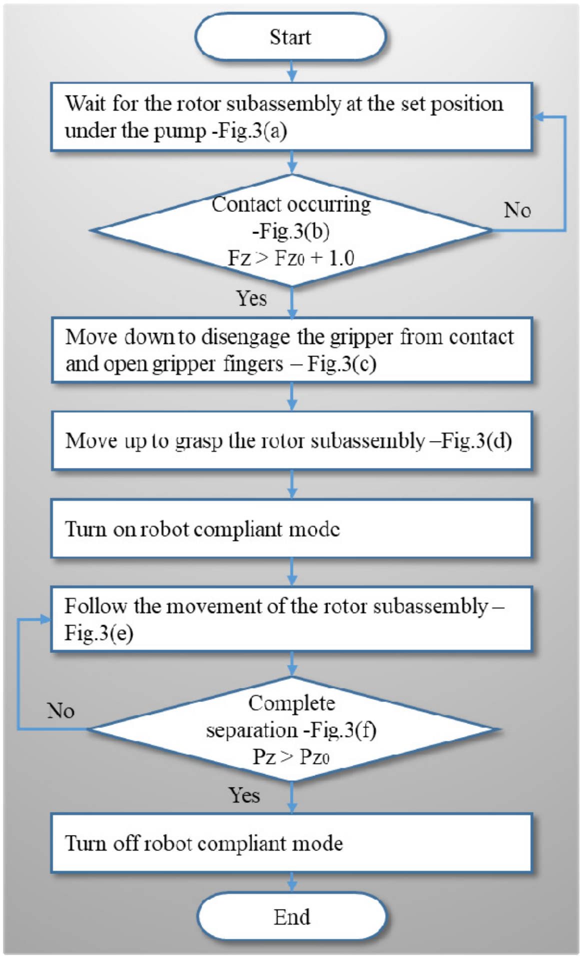

Figure 6. Flow chart of procedure.

Class "*HRCAB*" (line 1) describes the separation procedure and the contact force is set in class "*waitingforce*" (line 6). Class "*newstiffness*" (line 11) is designed to turn the robot compliance on and off according to the position feedback information during the disassembly process. Table 4 lists the values of translational stiffness and rotational stiffness of the robot during the disassembly process shown in Figure 5.

2.3 Results and discussion

The procedure described in the previous section was carried out in the demonstration cell shown in Figure 3. Figure 7 presents selected image frames captured from the process of separating the rotor subassembly from the flange and the pump casing.

The robot lifts the water pump and places it in the press fixture (Figure 7(a)). Once the pump is located and released, the robot positions the gripper below the fixture (Figure 7(b)) and waits for the press operator to extract the rotor subassembly from the flange and pump casing.

As the rotor subassembly is pressed out, it eventually contacts the gripper (Figure 7(c)), signalling to the robot to continue the disassembly operation. The robot lowers the gripper, taking it away from the rotor subassembly (Figure 7(d)), and then opens its fingers (Figure 7(e)). Next, the robot moves upwards before closing the gripper fingers to grasp the rotor subassembly (Figure 7(f)). As the press continues to force the rotor subassembly downwards, the robot holds on to it and compliantly tracks its motion. When the rotor subassembly is fully released, the robot takes control (Figure 7(g)), moving it away from the press. The robot finishes the disassembly operation by placing the subassembly on the workbench fixture (Figure 7(h)).

Figure 8 shows the HRC disassembly process for the water pump using the two collaborative robots in the second demonstrating cell (Figure 4). Preliminary trials show that the proposed HRC disassembly method is feasible. Work is being carried out to give the cell additional tools and capabilities, such as screwdrivers to remove threaded components and force/torque/vision sensors to enhance the cognitive ability of the robot, enabling it to collaborate even more effectively with the human operator.

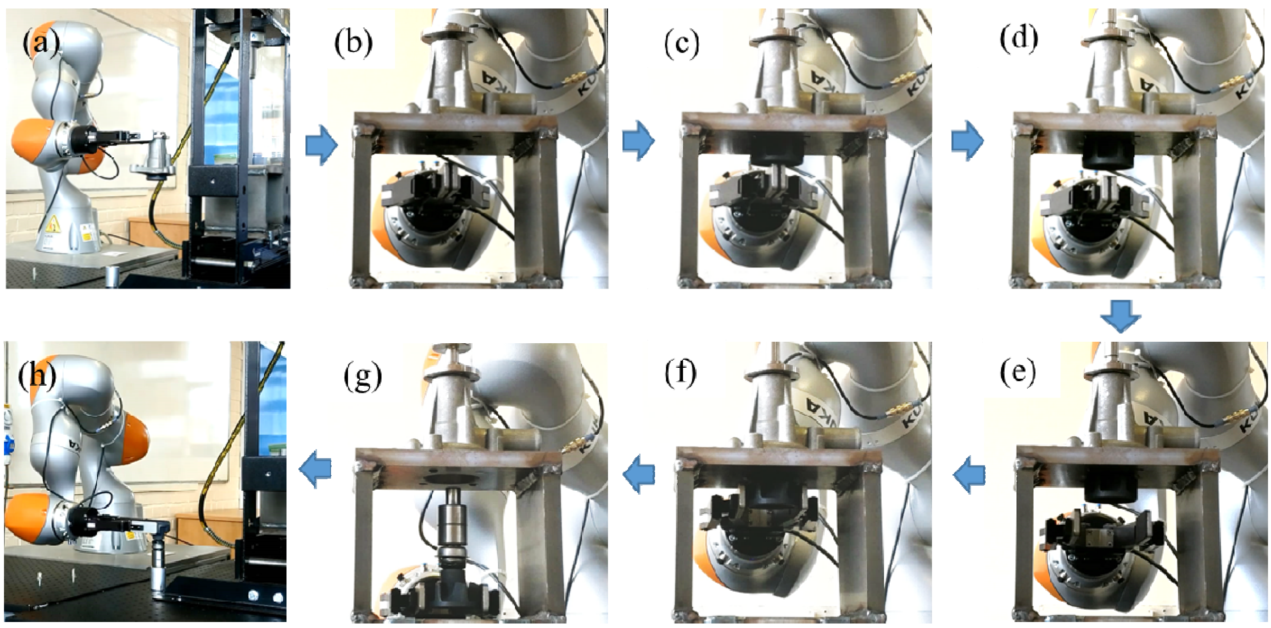

Figure 7. Separation of the rotor subassembly from the flange and pump casing.

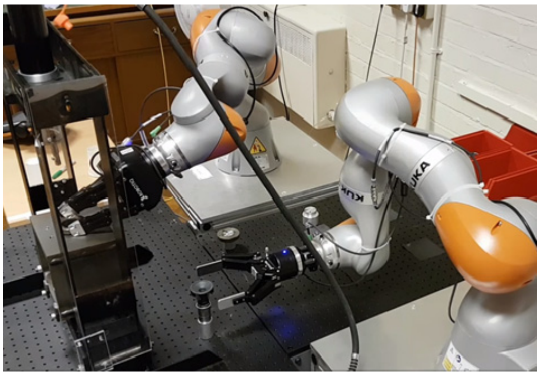

Figure 8. HRC disassembly of the water pump using two collaborative robots.

5. CONCLUSIONS

In remanufacturing, there are uncertainties due to unpredictability in the condition of the returned EoL products and variance in remanufacturing processes, which are main barriers to achieving autonomous disassembly. HRC disassembly as a semi-autonomous solution is aimed at achieving the flexibility and adaptability needed for cost-effectively dealing with those uncertainties. This paper has presented a strategy for HRC disassembly using active compliance control of collaborative robots. The collaborative robot uses its compliance facility to assist the human operator with complex disassembly tasks.

A case study has been carried out to demonstrate the successful applications of the proposed strategy and method in two HRC disassembly demonstration cells. The case study involved the disassembly of press-fitted components (the rotor subassembly, the flange and the pump casing) from an automotive water pump by a collaborative industrial robot working together with a human operator and by two collaborative robots and a human operator without requiring special safety measures.

APPENDIX

The disassembly of the water pump described in Section 4 can be viewed at: https://www.youtube.com/channel/UC19YoctUtyGAdazYFrYE1MQ.

ACKNOWLEDGMENT

This research is supported by the EPSRC (Grant No. EP/N018524/1) and the National Science Foundation of China (Grant No. 51775399). We thank Allan Tymen, Romain Delgres, Thibaud Thomas, Alix Le Quere, and Olivier Kabar from the Université de Brest for their contributions to the disassembly cell construction and demonstration. In addition, we acknowledge Michael Wright for his contributions to the design of robotic disassembly cell. This paper is an extended version of an article presented at Eighth International Conference on Business Sustainability 2018 in Portugal.

REFERENCES

[1] Sathish, T., J. Jayaprakash, P. V. Senthil, and R. Saravanan: *Multi Period Disassembly-to-Order of End of Life Product based on scheduling to maximize the Profit in Reverse Logistic Operation*, FME Transactions, Vol. 45, pp. 172-180, 2017.

[2] Kurilova-Palisaitiene, J., E. Sundin, B. Poksinska: *Remanufacturing challenges and possible lean improvements*, Journal of Cleaner Production, Vol. 172, pp. 3225-3236, 2017.

[3] Duflou, J. R., G. Seliger, S. Kara, Y. Umeda, A. Ometto, and B. Willems: *Efficiency and feasibility of product disassembly: A case-based study*, CIRP Annals-Manufacturing Technology, Vol. 57, pp. 583-600, 2008.

[4] Dimic-Misic, K., E. Barcelo, V. S. Brkic, and P. Gane: *Identifying the Challenges of Implementing a European Bioeconomy based on Forest Resources: Reality Demands Circularity*, FME Transactions, Vol. 47, pp. 60-69, 2019.

[5] Kim, H.-W., C. Park, D.-H. Lee: *Selective disassembly sequencing with random operation times in parallel disassembly environment*, International Journal of Production Research, pp. 1-15, 2018.

[6] Vongbunyong, S., S. Kara, and M. Pagnucco: *Application of cognitive robotics in disassembly of products*, CIRP Annals-Manufacturing Technology, Vol. 62, pp. 31-34, 2013.

[7] Vongbunyong, S. and W. H. Chen: *Disassembly automation*: Springer, 2015.

[8] Bentaha, M. L., O. Battaïa, A. Dolgui, and S. J. Hu: *Dealing with uncertainty in disassembly line design*, CIRP Annals - Manufacturing Technology, Vol. 63, pp. 21-24, 2014.

[9] Scholz-Reiter, B., H. Scharke, A. Hucht: *Flexible robot-based disassembly cell for obsolete TV-sets and monitors*, Robotics and computer-integrated manufacturing, Vol. 15, pp. 247-255, 1999.

[10] Gerbers, R., K. Wegener, F. Dietrich, and K. Dröder: *Safe, Flexible and Productive Human-Robot-Collaboration for Disassembly of Lithium-Ion Batteries*, in *Recycling of Lithium-Ion Batteries*, ed: Springer, pp. 99-126, 2017.

[11] Liu, Q., Z. Liu, W. Xu, Q. Tang, Z. Zhou, D. T. Pham: *Human-robot collaboration in disassembly for sustainable manufacturing*, International Journal of Production Research, pp. 1-18, 2019.

[12] Wegener, K., W. H. Chen, F. Dietrich, K. Dröder, and S. Kara: *Robot assisted disassembly for the recycling of electric vehicle batteries*, Procedia CIRP, Vol. 29, pp. 716-721, 2015.

[13] Chen, W. H., K. Wegener, and F. Dietrich: *A robot assistant for unscrewing in hybrid human-robot disassembly*, in Robotics and Biomimetics (ROBIO), 2014 IEEE International Conference on, pp. 536-541, 2014.

[14] Alvarez-de-los-Mozos, E., A. Renteria: *Collaborative robots in e-waste management*, Procedia Manufacturing, Vol. 11, pp. 55-62, 2017.

[15] Jungbluth, J., W. Gerke, P. Plapper: *An intelligent agent-controlled and robot-based disassembly assistant*, in Conference Proceedings on the 2nd

International Conference on Artificial Intelligence and Robotics (ICAIR 2017), p. 11, 2017.

[16] Cheng, H., W. Xu, Q. Ai, Q. Liu, Z. Zhou, and D. T. Pham: *Manufacturing Capability Assessment for Human-Robot Collaborative Disassembly Based on Multi-Data Fusion*, Procedia Manufacturing, Vol. 10, pp. 26-36, 2017.

[17] Gil, P., J. Pomares, S. v. P. C. Diaz, F. Candelas, and F. Torres: *Flexible multi-sensorial system for automatic disassembly using cooperative robots*, International Journal of Computer Integrated Manufacturing, Vol. 20, pp. 757-772, 2007.

[18] Mueller, R., M. Vette-Steinkamp, A. Kanso, and T. Masiak: *Collaboration in a Hybrid Team of Human and Robot for Improving Working Conditions in an Aircraft Riveting Process*, SAE Technical Paper, 0148-7191, 2019.

[19] De Santis, A. and B. Siciliano: *Safety issues for human-robot cooperation in manufacturing systems*, Tools and Perspectives in Virtual Manufacturing, 2008.

[20] Bo, H., D. M. Mohan, M. Azhar, K. Sreekanth, and D. Campolo: *Human-robot collaboration for tooling path guidance*, in Biomedical Robotics and Biomechatronics (BioRob), 2016 6th IEEE International Conference on, pp. 1340-1345, 2016.

[21] Khansari, M., E. Klingbeil, and O. Khatib: *Adaptive human-inspired compliant contact primitives to perform surface–surface contact under uncertainty*, The International Journal of Robotics Research, Vol. 35, pp. 1651-1675, 2016.

[22] Davies, B., S. Harris, W. Lin, R. Hibberd, R. Middleton, and J. Cobb: *Active compliance in robotic surgery—the use of force control as a dynamic constraint*, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, Vol. 211, pp. 285-292, 1997.

[23] Carrell, J., H.-C. Zhang, D. Tate, and H. Li: *Review and future of active disassembly*, International Journal of Sustainable Engineering, Vol. 2, pp. 252-264, 2009.

[24] Vongbunyong, S., P. Vongseela, and J. Sreerattana-aporn: *A Process Demonstration Platform for Product Disassembly Skills Transfer*, Procedia CIRP, Vol. 61, pp. 281-286, 2017/01/01/ 2017.

[25] Wright, M.: *Design of a Robotic Cell for Turbocharger Disassembly* University of Birmingham, 2018.

[26] COMAU. *AURA, Collaborative robots*, (2018). Available: https://www.comau.com/EN/our-competences/robotics/automation-products/CollaborativeRobotsAura

[27] Weber, A.: *Collaborative robot do's and don'ts*, (2018). Available: https://www.assemblymag.com/articles/94459-collaborative-robot-dos-and-donts

[28] Khatib, O.: *The Age of Human-Robot Collaboration*, in ROMANSY 22 – Robot Design, Dynamics and Control, Cham, pp. 1-9, 2019.

[29] Petrovic, P. B. and N. A. Lukic: *Configuration-based Compliance Control of Kinematically Redundant Robot Arm Part I - Theoretical Framework*, FME Transactions, Vol. 45, pp. 468-474, 2017.

[30] Xuan, W., L. Zhou, Y. Li, H. Chai, and H. Wang: *Controller design and experimental validation of a robot joint with active compliance*, in Chinese Automation Congress (CAC), 2017, pp. 5156-5160, 2017.

[31] Khan, S. G., G. Herrmann, M. Al Grafi, T. Pipe, and C. Melhuish: *Compliance control and human–robot interaction: Part 1—survey*, International Journal of Humanoid Robotics, Vol. 11, p. 1430001, 2014.

[32] Wang, W., R. N. K. Loh, and E. Y. Gu: *Passive compliance versus active compliance in robot□based automated assembly systems*, Industrial Robot: An International Journal, Vol. 25, pp. 48-57, 1998.

[33] Petrovic, P. and N. Lukic: *Configuration-based compliance control of kinematically redundant robot arm Part I: Theoretical framework*, FME Transaction, Vol. 45, pp. 468-474, 2017.

[34] Raibert, M. H. and J. J. Craig: *Hybrid position/force control of manipulators*, Journal of Dynamic Systems, Measurement, and Control, Vol. 103, pp. 126-133, 1981.

[35] Jamil, M. F. A., J. Jalani, and A. Ahmad: *A new approach of active compliance control via fuzzy logic control for multifingered robot hand*, in First International Workshop on Pattern Recognition, p. 9, 2016.

[36] GmbH, K. R.: *KUKA_SunriseOS 1.11*. Augsburg, Germany, 2016.

ЈЕДНА СТРАТЕГИЈА ЗА САРАДЊУ ЧОВЕК-РОБОТ У РАЗДВАЈАЊУ ПРОИЗВОДА ЗА РЕ-ПРОИЗВОДЊУ ПРИЛИКОМ ДЕМОНТАЖЕ

Џ. Хуанг, Д. Труонг Фам, Ј. Ванг, Ч. Џи, В. Шу, К. Лиу, Џ. Џоу

Коришћење људи и робота који заједно раде на демонтажи производа на крају животног века, тако да се они могу поново уђу у ре-производњу, омогућава подршку за ефекте неизвесности у стању тих производа и непредвидљивост у операцијама ре-производње. Колаборативни роботи су један од кључних елемената индустрије 4.0.
Овај рад представља стратегију за човек-робот колаборативну демонтажу која користи способност активне контроле усклађености колаборативних робота. У раду је приказан нацрт предложене стратегије сарадње човек-робот и активне контроле усклађености. Затим је представљена студија случаја роботске демонтаже која је пројектована да покаже практичну имплементацију предложене стратегије за раздвајање производа. Студија је обухватила демонтажу аутомобилске пумпе за воду

помоћу колаборативног индустријског робота који ради са оператором робота и два колаборативна робота и оператера робота. Активна контрола усклађености је имплементирана како би се одвојиле компоненте уграђене у пумпи пресовањем. Резултати демонстрирају изводљивост стратегије и њену ефиктивност у повећању флексибилности и прилагодљивости смањењем напора у припреми.